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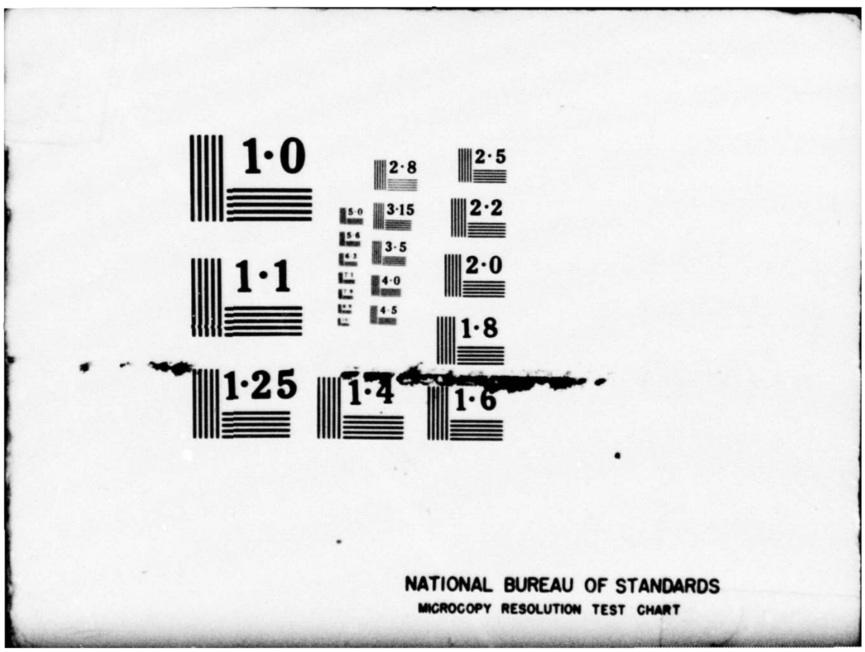
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AFOSR-TR- 78-0548

AFOSR FINAL SCIENTIFIC REPORT

SOLID PROPELLANT ADMITTANCE MEASUREMENTS
BY THE DRIVEN TUBE METHOD

Prepared for

Air Force Office of Scientific Research
Aerospace Sciences Directorate
Arlington, Virginia

by

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Approved for public release; distribution unlimited

Grant No. AFOSR-73-2571 October 1977

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: AFOSR-TR-78-0548

2. GOVT ACCESSION NO.:

3. RECIPIENT'S CATALOG NUMBER:

4. TITLE (and Subtitle): SOLID PROPELLANT ADMITTANCE MEASUREMENTS BY THE DRIVEN TUBE METHOD.

5. TYPE OF REPORT & PERIOD COVERED: FINAL rept. 30 Jun [redacted] 73 - 30 Sep 77

6. PERFORMING ORG. REPORT NUMBER:

7. AUTHOR(s): B. T. ZINN, M. SALIKUDDIN, B. R. DANIEL, W. A. BELL

8. CONTRACT OR GRANT NUMBER(s): AFOSR-73-2571

9. PERFORMING ORGANIZATION NAME AND ADDRESS:
GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF AEROSPACE ENGINEERING
ATLANTA, GEORGIA 30332

403 914

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 2308A1, 61102F

11. CONTROLLING OFFICE NAME AND ADDRESS:
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH/NA
BLDG 410
BOLLING AIR FORCE BASE, D C 20332

12. REPORT DATE: Oct 77

13. NUMBER OF PAGES: 37

40 p.

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office):

15. SECURITY CLASS. (of this report): UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:

16. DISTRIBUTION STATEMENT (of this Report):

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report):

18. SUPPLEMENTARY NOTES:

19. KEY WORDS (Continue on reverse side if necessary and identify by block number):
COMBUSTION INSTABILITY
SOLID PROPELLANT RESPONSE FUNCTIONS
SOLID PROPELLANT ROCKETS
IMPEDANCE TUB MEASUREMENTS

20. ABSTRACT (Continue on reverse side if necessary and identify by block number):

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ABSTRACT

The progress made during the fourth year of an investigation for the measurement of the response of a burning solid propellant to flow disturbances is presented. In this study a modification of the impedance tube technique is used to measure the response over a wide frequency range. Further refinements in the data reduction computer program are discussed. Anomalous behavior for high pressure (300 psig) tests which shows that the propellant sample periodically drives and damps acoustic oscillations during a burn was resolved. Techniques for improving the accuracy of the measured data and the quality of the burn have been developed. Testing will resume during the next year.

INTRODUCTION

This report summarizes the objectives, research performed and results obtained under Air Force Grant No. AFOSR-73-2571. This grant was initiated on July 1, 1973 and it has been concerned with the "Determination of the Acoustic Responses of Solid Propellants by the Impedance Tube Method." This research is presently continuing under Air Force Contract F49620-78-C-0003.

Combustion instability has been recognized as one of the most serious problems encountered in the development of solid-propellant rockets. Combustion instability is the result of an interaction between the combustion process and disturbances within the rocket motor; an interaction which often leads to the amplification of these disturbances into finite amplitude oscillations. The appearance of combustion instability frequently produces dramatic and even catastrophic changes in the motor's performance. Combustion instability may also result in mechanical failure of engine components, extremely high heat transfer rates to the combustor boundaries and interference with the control and guidance systems. Any one of these effects can result in engine or mission failure.

To determine the susceptibility of a given propulsion system to combustion instability, it is necessary to determine the energy balance that exists between the various gains and losses of wave energy present within the combustor. Wave energy loss mechanisms tend to attenuate the amplitude of a disturbance in the combustor and thus exert a stabilizing influence upon the engine. Examples of wave energy loss mechanisms are convective energy losses caused by the mean flow, energy dissipation associated with viscosity and heat transfer, energy dissipation due to wave interaction with particulate matter, and energy losses resulting from the interaction of the disturbance with various mechanical components of the engine such as

the exhaust nozzle. On the other hand, wave energy gains tend to amplify engine disturbances and thus exert a destabilizing influence upon the combustor. The primary source of wave energy gain is the unsteady combustion process. If the energy gains are greater than the wave energy losses in the motor, an initial disturbance will amplify and lead to undesirable self-sustained oscillations inside the combustor. To evaluate the stability of a solid-propellant rocket motor, it is necessary to quantitatively describe the various gain and loss mechanisms that are present in the system.

The wave energy gain in a solid rocket may be determined from either a theoretical or an experimental investigation of the interaction between a burning solid propellant and an oscillating gas phase. This interaction can be described mathematically by specifying either the response factor or the admittance of the burning solid propellant surface. The admittance represents the boundary condition which must be satisfied at the burning propellant boundary in solid rocket stability analyses. The admittance is defined as the complex ratio of the gas velocity perturbation normal to the surface and the local pressure perturbation. The nondimensional form Y_b of the admittance of a burning propellant is often expressed in the following form:

$$Y_b = \frac{\gamma \bar{P}}{\bar{c}_b} \cdot \frac{u'}{P'} \tag{1}$$

γ, P, u and c respectively describe the ratio of specific heats, pressure, flow velocity and sound velocity; primed quantities describe flow perturbations and superposed bars describe steady state quantities. The earlier mentioned propellant response factor R_b is defined as the complex ratio of the propellant burning rate perturbation to the pressure perturbation,

evaluated at the burning surface. The nondimensional form of the response factor is:

$$R_b = \frac{\bar{\bar{P}}}{\bar{\bar{r}}} \cdot \frac{r'}{P'} = \frac{\bar{\bar{P}}}{\bar{\bar{m}}} \cdot \frac{m'}{P'} \tag{2}$$

where r and m respectively describe the propellant regression rate and the gas flow rate at the propellant surface.

The relationship between the propellant response factor and its admittance is often of interest. The mass flux m at the burning surface is given by

$$m = \rho u = \rho_s r \tag{3}$$

It follows from Eq. (3) that

$$\frac{m'}{\bar{\bar{m}}} = \frac{\rho'}{\bar{\rho}} + \frac{u'}{\bar{\bar{u}}} \tag{4}$$

and using Eqs. (1), (2) and (4) one can easily show that:

$$R_b = \frac{Y_b}{\gamma \bar{\bar{M}}_b} + \frac{\rho'/\bar{\rho}}{P'/\bar{\bar{P}}} \tag{5}$$

If the oscillations are isentropic, then

$$\frac{\rho'}{\bar{\rho}} = \frac{1}{\gamma} \frac{P'}{\bar{\bar{P}}} \tag{6}$$

and Eq. (5) reduces to the following expression:

$$R_b = \frac{1}{\gamma \bar{\bar{M}}_b} [Y_b + \bar{\bar{M}}_b] \tag{7}$$

The above quantities will be used later in this report in the presentation of some of the data measured under this program.

Since instability is often caused by small differences between wave energy gains and losses, it is imperative that the contributions from all processes affecting the stability of rocket engines be known as accurately as possible. Hence, it is of utmost importance that experimental techniques capable of accurate determination of the responses of burning solid propellants be available. The development of such an experimental technique was one of the main objectives of this research which has been concerned with the adaptation of the impedance tube method in the determination of the responses of burning solid propellants. The impedance tube technique has its origin in acoustics where it has been successfully utilized to measure the responses of sound absorbing materials under no flow conditions.[(1)] This technique was later modified to determine the responses of choked rocket nozzles[(2)] and acoustic liners[(3)] under cold flow conditions. It has been chosen as a potential means for the measurement of the admittances of burning solid propellants because (1) it offers the possibility for accounting for the influence of aluminum particles in both the combustion zone and gaseous phase; (2) the possibility of carefully controlling the frequency and growth rate of the oscillation; and, (3) contrary to T-burner type experiments, the same setup may be used to study the response of a given solid propellant over a whole frequency range and fewer tests are potentially needed than with any of the T-burner type experiments. A more detailed description of the impedance tube experiment is provided in the following section.

Considerable modifications to the classical impedance tube technique were necessary for use in the measurement of the admittances of burning solid propellants. In contrast with earlier applications[1,2,3] of this technique, the present application involves admittance measurements under

high pressure and temperature conditions . To achieve this objective, a new experimental facility capable of operation under high pressure and temperature was designed and fabricated; a new impedance tube theory accounting for the presence of a temperature gradient in the impedance tube was developed, a new experimental procedure was implemented; a new data reduction procedure utilizing a nonlinear reduction technique was employed; an analog-to-digital data acquisition system was developed; and numerous tests involving a variety of solid propellants have been conducted over a wide range of operating conditions. The work performed under this grant has described in detail in earlier interim reports[4,5,6] JANNAF publications[7,8] and an AIAA publication[9]. Additional publications based upon this work are currently in the planning stage. In what follows brief descriptions of what has been accomplished to date and future directions of this work are provided. This section is followed by a section describing the impedance tube technique, the theoretical aspects of the research, the experimental setup, the data reduction procedure, results obtained to date, and the current status of the program.

The Impedance Tube Technique

In the past the impedance tube has been used to measure the admittances of various sound absorbing materials. In such studies, the experimental setup (see Figure 1) consists of a tube with an acoustic driver at one end and the sample whose admittance is to be measured at the other end. During an experiment, the driver generates an incident wave P_i of a given frequency ω that propagates along the tube until it impinges upon the tested sample. Because of the interaction between the incident wave and the sample material, the incident wave reflects off the tested sample with modified amplitude and phase. The reflected wave P_r then combines with the incident wave to form a

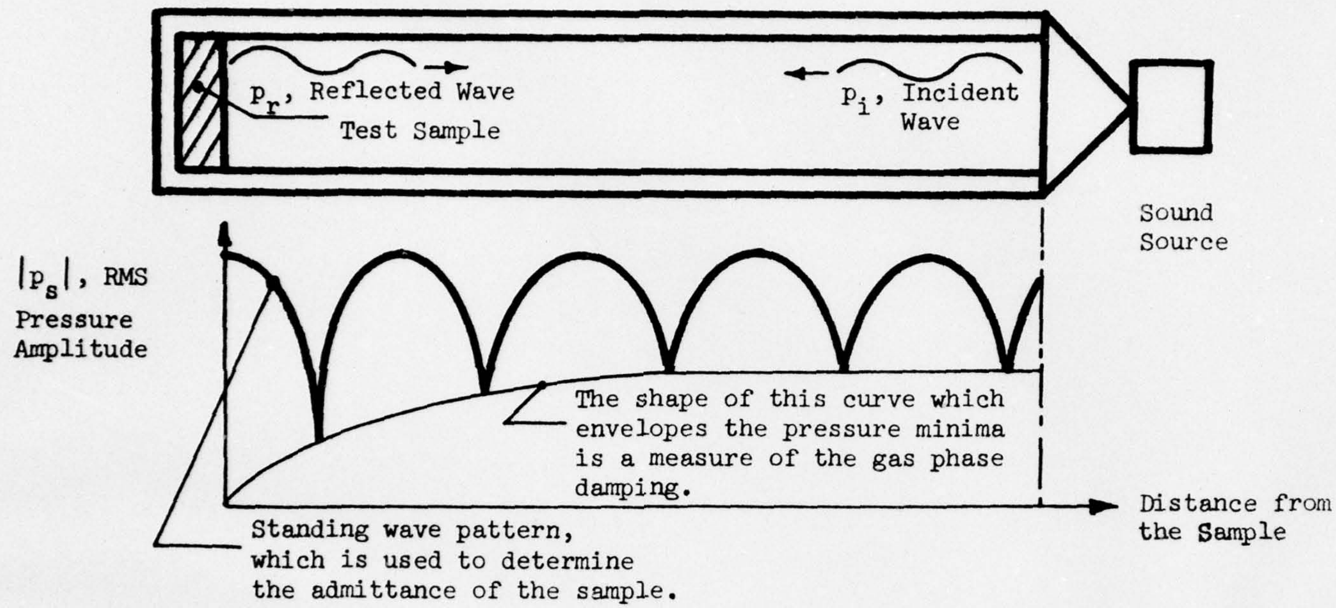

Figure 1. An Impedance Tube and a Typical Standing Wave Pattern

standing wave pattern in the tube whose structure depends, among other things, upon the admittance of the tested sample. It can be shown,[(2),(10)] that the sample admittance Y depends upon two parameters, α and β, which respectively describe the changes in amplitude and phase between the incident and reflected waves at the sample surface, that is

$$Y = \frac{u'}{p'} = f(\alpha, \beta, \omega, \ldots) \tag{8}$$

where f is a known functional form. The admittance Y can be determined once the parameters α and β are known. It can also be shown[(2),(10)] that the structure of the amplitude $|P(x)|$ of the standing wave in the tube can be described by an expression having the following functional form:

$$|P(x)| = g(\alpha, \beta, \gamma, \lambda, x \ldots) \tag{9}$$

where γ is a measure of attenuation of the waves due to acoustic energy losses in the gas phase, λ is the wave length of the oscillation and x describes the axial location in the tube. In impedance tube experiments a microphone is traversed along the tube to measure $|P(x)|$. Once this data is available, it can be used together with the above equation to determine the unknowns α, β and γ. The quantities α and β are then used to determine Y. This technique has recently been successfully applied to measure the admittances of choked nozzles in the presence of a mean flow[(2),(3)]. This data provides a measure of the attenuation provided[(11)] by choked nozzles during axial and three-dimensional instabilities.

To be applicable in solid propellant admittance measurements, the classical impedance tube setup and its associated theory need to be modified to account for the presence of a mean flow and a steady state temperature in the impedance tube during the experiment. These requirements con-

siderably complicate the execution of the required experiment and the associated data reduction scheme, as will be discussed in the following sections.

THEORETICAL INVESTIGATIONS

The theoretical efforts conducted under this program fall into the following two categories:

(1) Development of an analytical procedure for the utilization of measured acoustic pressure (amplitude and phase) data in the determination of the response factor and admittance of a burning solid propellant and

(2) Investigation of the wave behavior in the impedance tube under the range of conditions expected in the proposed solid propellant admittance measurements.

The first category above basically represents a modification of the classical impedance tube theory. This modification required the development of an analytical procedure capable of utilizing acoustic pressure data measured at discrete locations along the impedance tube, and accounting for a steady state temperature gradient and possibly gas phase acoustic energy dissipation, in the determination of the response factor and admittance at the burning solid propellant surface. It is basically an inverse problem; that is, the boundary condition at the burning solid propellant surface that results in the measured acoustic wave structure.

Before proceeding with a discussion of the developed data reduction procedure it is necessary to discuss some of the constraints imposed by the presence of high temperatue combustion products in the tube and the relatively short "burn time" of the tested solid propellant sample. These effects restrict the data acquisition time to a period of one or two seconds, which is too

short a period for traversing a microphone probe along the impedance tube. Thus, in the present study the traversing microphone used in the classical impedance tube setup is replaced by ten microphones which increase the acoustic pressures at preselected fixed locations along the impedance tube throughout the duration of the test. These data are used in the determination of the acoustic wave structure and the admittance at selected time intervals during the test. The method of measurement offers the possibility of determining the unknown solid propellant admittance as a function of time.

The procedures utilized in the development of the data reduction procedures are described in detail in Refs. 4 through 8. Briefly, the initial program efforts concentrated on the derivation of the conservation equations describing the behavior of the waves in the tube while accounting for the presence of a steady state temperature gradient and gas phase acoustic losses. Next, a numerical solution technique for the derived equations and a procedure for determining the steady state temperature distribution were developed. Assuming periodic time dependence for the dependent variables (e.g., $p' \alpha e^{i\omega t}$), the time dependence was "separated" out from the system of one dimensional wave equations and the latter was reduced to a system of coupled ordinary differential equation in the axial variable x. The latter could be solved numerically once the x distribution of the steady state variables and the initial conditions at a given location, say x_0, were known. However, the determination of these initial conditions is the objective of the proposed experiment and their determination is the focus of the proposed data reduction procedure, as is discussed below.

It can be shown[4] that the complete steady state flow behavior can be determined once the x distribution of one of the dependent variables, say the temperature $\bar{T}(x)$, is known. Considerable effort has been expended under

this program on the development of an accurate and efficient method for the determination of $\bar{T}(x)$. The determination of $\bar{T}(x)$ by either direct thermocouple measurements or through wave length measurements were discarded, after some study, due to their inaccuracies and associated experimental difficulties. After investigating this problem for awhile it had been concluded that the appropriate distribution of $\bar{T}(x)$ should be determined by using the nonlinear regression technique, as will be described shortly. In this case the developed data reduction scheme determines, in addition to the unknown admittance, the temperature distribution $\bar{T}(x)$ that provides the optimum fit between the measured acoustic pressure data and the solution of the impedance tube wave equations. Description of the above mentioned efforts can be found in Refs. 4 through 8.

The solutions of the impedance tube wave equations can be expressed in the following functional form

$$p' = f(x, \omega, \bar{T}(\Lambda), u_o', \rho_o', p_o') \tag{10}$$

where x, ω, Λ respectively represent axial variable, frequency and a steady state heat transfer parameter and the subscripted variables describe a set of initial conditions. Incidentally, the steady state temperature distribution is determined once Λ is known[4,6].

The admittance and response factor at the burning propellant surface are determined in this program by determining the set of initial conditions u_o', p_o' and ρ_o', at some location in the impedance tube, and heat transfer parameter Λ that provides the best fit between the measured acoustic pressures and the solution of the wave equations for the impedance tube. Once this set of optimum initial conditions is found at some location in the tube the

corresponding set of dependent variables at the propellant surface can be readily found by integrating the tube wave equations from the chosen initial point x_o to the propellant surface. The calculated set of values for p',ρ' and u' and the corresponding steady state solutions can then be substituted into Eqns. (1) and (5) to determine the propellant admittance and response factors.

A nonlinear regression (NLR) has been utilized to determine the desired unknowns. In this case the optimum set of p_o', ρ_o', u_o' and Λ are found by determining the set of values that minimizes the following positive quantity

$$E = \sum_{i=1}^{N} \left\{ |P_T(x_i,\omega,\bar{T}(\Lambda),\ P_o',\ \rho_o',u_o')| - |P_E(x_i)| \right\}^2$$

$$+ \sum_{i=1}^{N} \left\{ \varphi_T(x_i,\omega,\bar{T}(\Lambda),\ P_o',\rho_o',u_o') - \varphi_E(x_i) \right\}^2 \qquad (11)$$

where the quantities N, $|P|$ and φ represent the number of experimental measurements, the i^{th} measurement location, the pressure amplitude and the pressure phase, while the subscripts T and E respectively describe theoretically and experimentally determined quantities. Carrying out the above minimization procedure requires the use of such concepts as "transmission matrices" and the development of iterative solution schemes for a system of nonlinear algebraic equations. The details of development of these solution techniques and description of their applications in the determination of the admittances of burning solid propellants can be found in Ref. 6.

Since its development under this program, the above-mentioned data reduction program has been applied successfully in a NASA sponsored program that was concerned with the determination of the admittances of coaxial gaseous injectors utilizing acetylene-air and methane-air as the fuel-oxydizer combinations. Descriptions of these investigations can be found in Refs. 12 and 13.

The second aspect of the theoretical studies conducted under this program was concerned with the investigation of the dependence of the impedance tube wave structure upon the various parameters (i.e., see Eq. (10)) that appear in the impedance tube wave equations. This investigation has been undertaken in order to develop an understanding that could be used in the interpretation of observed experimental trends. To accomplish this objective, various parameters that appear in the wave equations were varied systematically and the corresponding acoustic wave structure was determined by numerically solving the developed system of impedance tube wave equations. Parameters varied in this study included the magnitude of the real and imaginary parts of the admittance at the propellant surface, the gas phase losses and the heat transfer parameter Λ. The resulting variations in the computed acoustic wave structure were analyzed and compared with observed experimental trends. These comparisons provided considerable insight into the acoustic behavior of the developed impedance tube. More detailed descriptions of these experimental investigations can be found in Refs. 4 and 5.

The wave equations considered to date in the above-mentioned investigations included the effects of steady state temperature gradients and gas phase damping. Another phenomenon that could possibly affect the

impedance tube wave structure is the oscillatory heat transfer to the impedance tube walls. The effect of this phenomenon upon the measured impedance tube wave structure may have to be investigated in the future to determine whether this phenomenon needs to be included in the data reduction procedure.

In summary, the theoretical efforts conducted under this program to date have extended the theoretical foundation of the classical impedance tube technique to account for the presence of mean flow and a temperature gradient in the tube. The developed theory was then used in the development of data reduction procedure which acoustic pressure measurements taken at discrete locations along the impedance tube can be used to determine the admittance at the propellant surface. This is in contrast with the classical impedance tube technique where a traversing microphone is used to determine the wave structure in the impedance tube. Finally, an investigation of the dependence of the wave equations solutions upon the various parameters which appear in these equations provided considerable assistance in the interpretation of the experimental data.

EXPERIMENTAL EFFORTS

A. Developed Experimental Setups

The experimental efforts conducted under this program were divided into two phases with the initial phase being concerned with propellant admittance measurements under atmospheric pressure conditions and the second phase being concerned with propellant admittance determination under high pressure conditions. The atmospheric pressure studies were undertaken in order to minimize the difficulties associated with the initial development of the experimental technique. The atmospheric pressure experimental apparatus is shown schematically in Fig. 2 and its detailed description can be found in Ref. 4. Also included in Ref. 4 are plots of typical measured acoustic pressure data and steady state temperature distributions.

As solid propellant rockets normally operate under high pressure conditions, it becomes necessary to obtain propellant admittance data under high pressure conditions. Consequently the second phase of this program was concerned with the development of an experimental facility that could be utilized for propellant admittance measurement in the range 0-500 psig. A schematic of the high pressure facility is shown in Fig. 3. The impedance tube* with the propellant sample-holder, the pressure transducer, and the acoustic driver are all contained within the 0 to 500 psig pressurization tank which is equipped with high pressure hinged ports to allow easy access for propellant sample changes, burner tube removal, and maintenance.

Air supply for tank pressurization and the flow requirements of the

* In the present study the impedance tube has often been referred to as the driven tube burner.

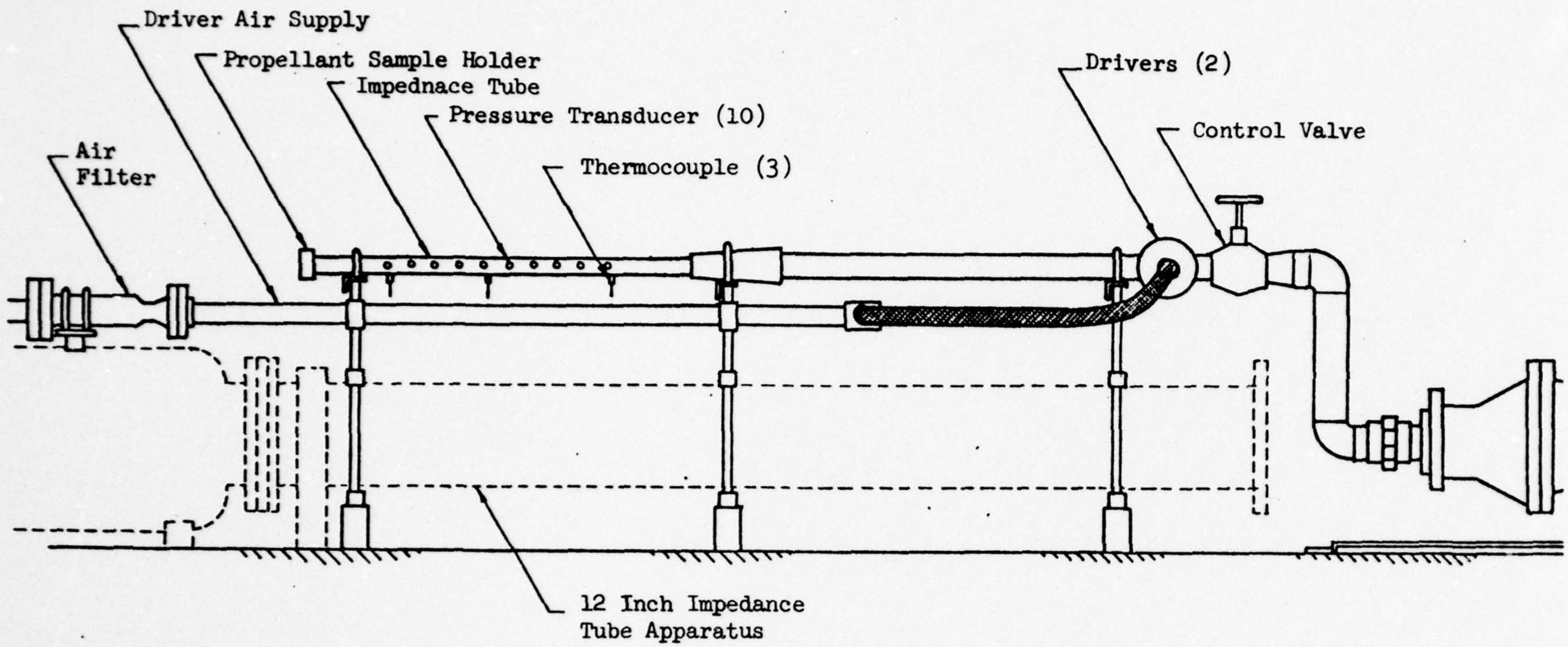

Figure 2. Sketch of the General Arrangement of the Unpressurized Driven Burner Experiment

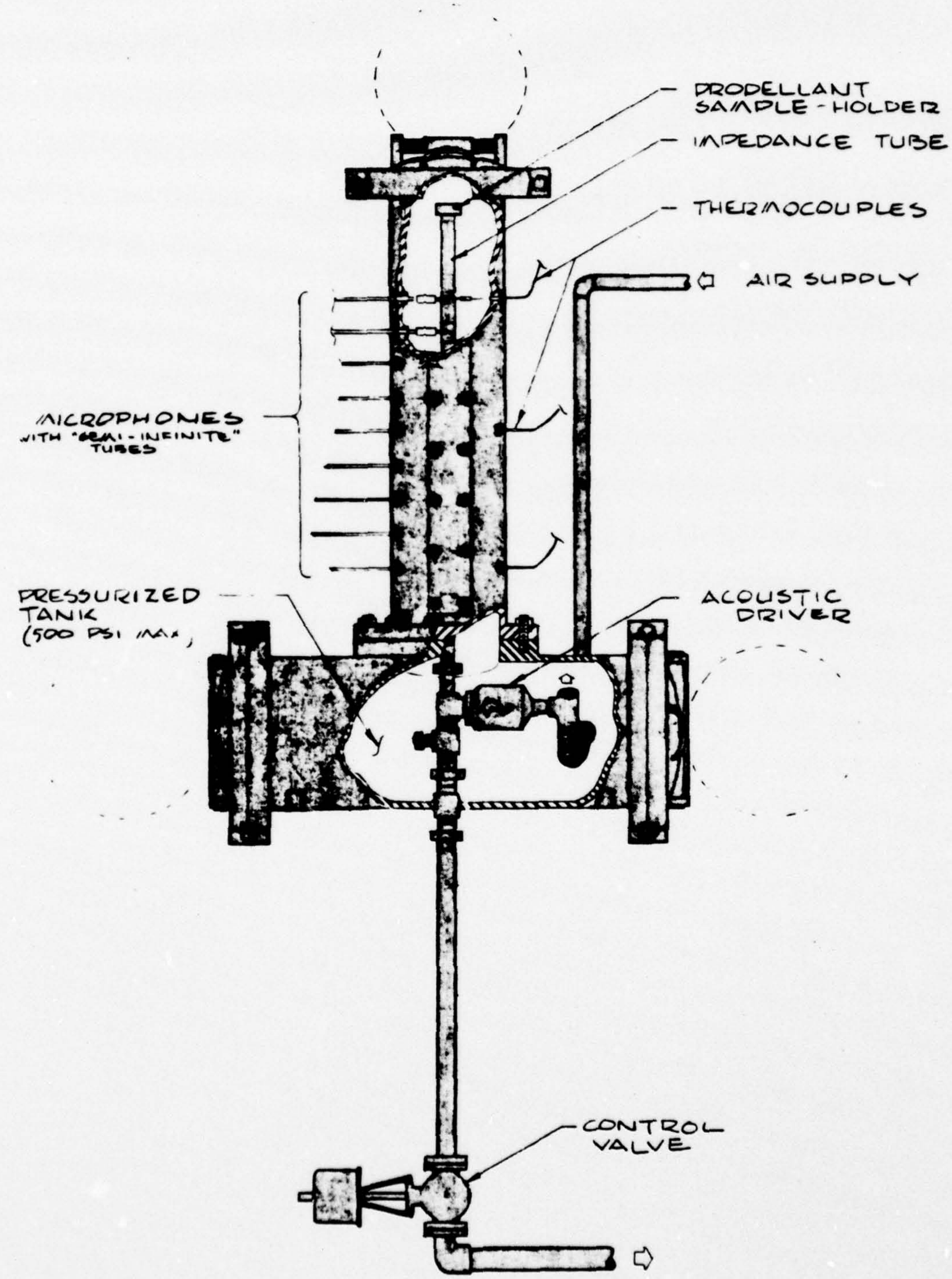

Figure 3. Schematic Diagram of Pressurized Driven Burner Facility

electropneumatic driver is provided by a 3000 psig, 500 cu.ft. blow down facility. The tank pressure and driver airflow are maintained by a pressure control valve in the exhaust line of the system as shown in the schematic of the flow system in Fig. 4.

The components of the high pressure driven burner tube facility and the principles of its operation are basically unchanged from the low pressure facility previously in operation. The impedance tube contained in the high pressure tank was fabricated from a stainless steel pipe with a two inch inside diameter. Provisions for a propellant sample holder are included on one end and an acoustic driver capable of developing 4,000 watts of acoustic power is close-coupled to the tube on the other end. Provisions for instrumentation (pressure and/or temperature measurements) have been included along six feet of the tube wall. The instrumentation locations are one-quarter inch apart measured from the face of the propellant sample. During a test, the propellant sample is ignited by a nichrome wire glued to the sample surface in an "S" shape. To assure a rapid and uniform ignition of the propellant, the surface of the sample is coated with a thin pyrotechnic mixture comprised of 72.4% potassium perchlorate, 14.8% titanium, 6.9% Boron powder, and 6.0% polyisobutylene binder dissolved in toluene. For ignition the nichrome wire is heated by a 40 volt, 15 ampere power supply. Measuring the standing wave pattern in the driven burner tube with a burning solid propellant sample imposes stringent requirements on the instrumentation. The pressure and high temperature pose the problem of protecting the highly sensitive transducer diaphragms from the hot gases in the tube. Various methods for the protection of the transducers have been investigated. The semi-infinite tube technique utilized in the atmospheric pressure studies[4,5] has proven unsatisfactory for high pressure operation because of a low frequency

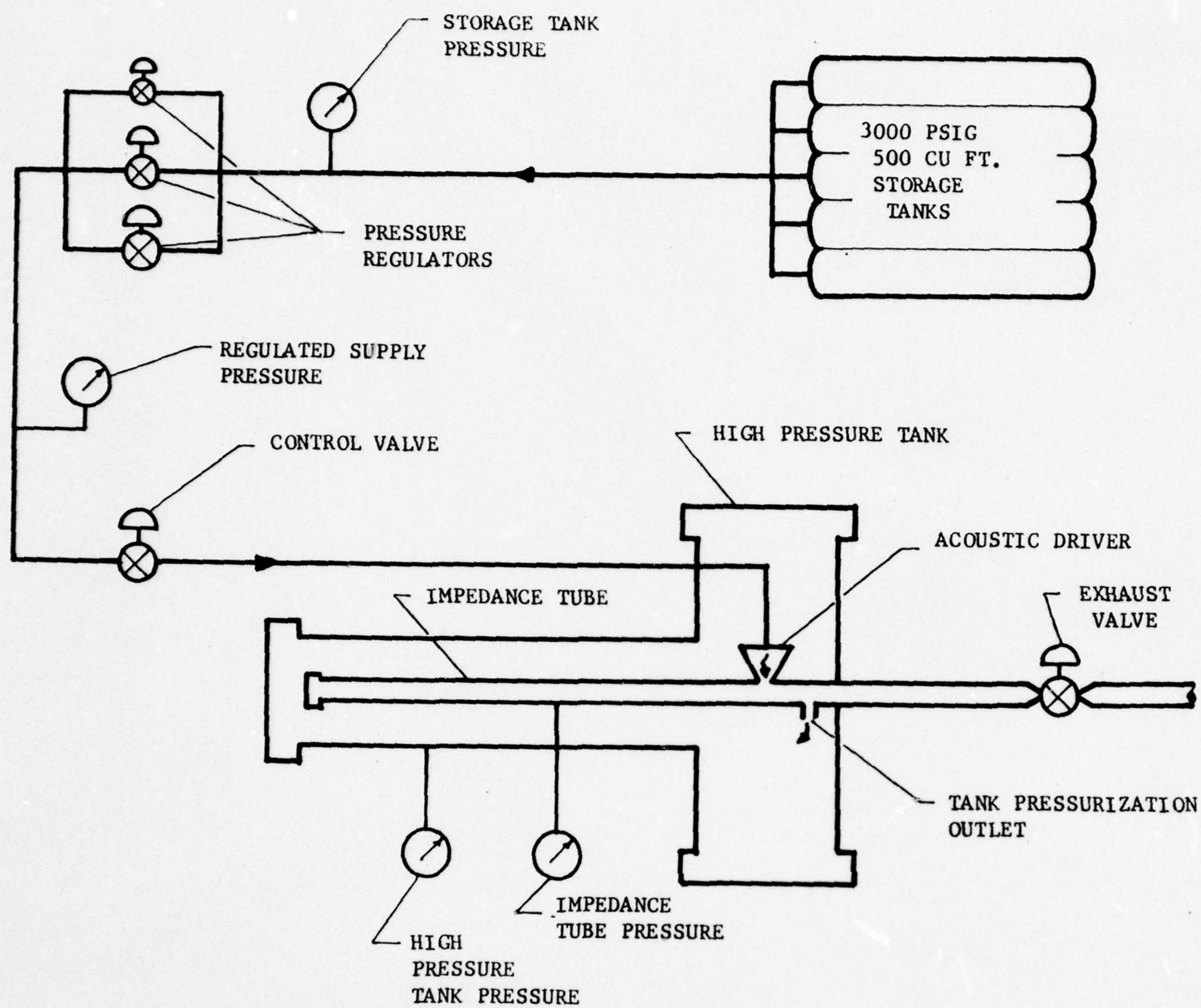

Figure 4. Schematic of Facility Flow System

resonance in the infinite tube at high pressures. Instead a short pressure transducer adaptor has been utilized in the high pressure investigation.[6] Further protection for the transducer is provided by a thin coating of clear silicone grease applied to the transducer diaphragm. Extensive calibration and testing of this short transducer adapter has been conducted and the results indicate that in the frequency range of interest for this experiment, (i.e., 300 Hz to 1100 Hz), the adapter provides highly satisfactory pressure amplitude and phase measurement characteristics.

The acoustic driver used in the high pressure driven burner tube is a Ling ETP-94 B electropneumatic driver capable of developing 4,000 watts of acoustic power which provides a sound pressure level of 170 decibels in the burner tubes. The driver is close-coupled to the tube wall at the downstream end of the burner tube. The frequency and waveform output of the acoustic driver is controlled by a Spectral Dynamics Oscillator, Model SD104A-5. For this investigation, the waveforms of the pressure oscillations are sinusoidal and the frequency of the oscillations are constant during a given test.

Small modifications to the developed experimental setup have been introduced in the course of this study. These modifications included changing the nature of the termination at the exhaust end of the tube and the utilization of both short (i.e., 4 feet) and long (i.e., 10 feet) impedance tubes. The nature of the exhaust termination was modified in order to assess the effect of the acoustic properties of the exhaust end upon the impedance tube acoustic wave structure and the four feet impedance tube was utilized in order to assure that both the acoustic driver and the pressure transducers are "located" within the hot combustion products shortly after ignition. When this condition is not satisfied, the measurement of the hot-cold

gas interface toward the acoustic driver results in periodic resonances in the impedance tube and amplitude variations of the standing acoustic wave within the impedance tube.

B. Test Procedures.

The data acquisition system and the equipment to establish and monitor test conditions are located in a laboratory area adjacent to the room housing the high pressure driven tube experiment. Test conditions are established by slowly pressurizing the high pressure tank housing and the burner tube to the desired operating pressure. The pressurization tank pressure and driver airflow requirements are maintained by the tank pressurization control valve in the exhaust line. With tank pressure stabilized and a standing waveform of a desired frequency established a test run is initiated. The data acquisition period of a test run includes four phases; a brief pre-ignition test period with the acoustic drivers on and test conditions established in the burner tube, ignition of the propellant sample, the propellant "quasi-steady" burning period and the propellant extinguishment phase. The data acquisition period is normally about two and one-half seconds. A more detailed discussion of the data acquisition and data reduction procedures are presented in the following section.

C. Minicomputer-Based Data Acquisition System

A minicomputer-based data acquisition system has been incorporated in the program to obtain improved pressure and temperature data. This system processes the data in three stages. First, during a test the analog signals from the transducer and thermocouple channels are sampled, digitized, and stored at a controlled rate. Next, the stored readings are processed by the computer. The transducer data are digitally filtered and pressure amplitude

and phase data are obtained at the frequency of interest. Likewise, thermocouple signals are converted to temperatures. Finally, the pressure and temperature data are printed out and plotted. These values are then used in the data reduction scheme described in Section II to obtain the admittance values. A more detailed description of this data acquisition system is presented in Ref. 6.

As reported in Ref. 6, the results obtained using this data acquisition system indicated that the propellant was alternately driving and damping during a burn. To check this anomaly, the signals from the pressure transducers and thermocouples were also recorded on a 14-channel Ampex tape recorder. These data were then played back at reduced speed and plotted to provide a time history of the sound pressure levels, phase relationship, and temperature of the hot gases inside the tube. These plots were then compared with the corresponding plots obtained from the computer - based data acquisition facility. The results of this comparison are presented in the following section.

EXPERIMENTAL RESULTS

Because of stringent requirements on the accuracy of the pressure amplitude and phase measurements, the major thrust of the work during this reporting period has been directed toward improving the quality of these data.

As explained in the preceeding sections, the response of a burning solid propellant in a driven tube can be determined from pressure amplitude, phase, and temperature measurements taken along the standing wave in the tube. The ratio of the minimum to maximum pressure amplitudes of the standing wave is a measure of the amount of amplification or attenuation of an acoustic oscillation by the burning solid propellant. This ratio decreases with decreasing admittance or propellant response. Since the propellants which are under investigation in this study have nondimensional admittance values on the order of 10^{-2}, the difference between the maximum and minimum amplitude during an experiment is typically 40 decibels or more. To obtain reliable results for this range of amplitudes, the data acquisition and reduction instrumentation must have a large dynamic range. By measuring the phase differences between successive points along the tube, it is possible to determine whether the sample is amplifying or attenuating the incident wave from the driver and by how much. However, the phase differences between successive points along the standing wave for nondimensional admittance values on the order of 10^{-2} is small (less than two degrees) except near the pressure minima where the amplitude is low and the noise to signal ratio of the transducers high. Thus, great care must be exercised to ensure data reliability.

In Figs. 5 and 6 data are presented for a test conducted at 742 Hz with an A-13 propellant with a closed-ended exhaust configuration.[6] Figure 5 is a plot of the pressure amplitudes in decibels (re 2×10^{-4} microbars) versus record number for three pressure channels located at different axial stations along the tube. Each record represents a short time interval during which data was recorded by the analog-to-digital converter. Consecutive records correspond to consecutive time instances with about 30 milliseconds between records; therefore the abscissa represents time.

The total duration of a typical experiment can be divided into four distinct periods: (1) the preignition period during which the Ling acoustic drivers are the only source of wave excitation (e.g. records 1 to 14 in Figs); (2) the propellant ignition phase (records 15 to 20); (3) the quasi-steady burning phase during which the pressure data are used to determine the burning solid propellant admittance values (records 21 to 40); and (4) the burnout phase (records 41 to 80). During the ignition and burnout phases, the temperature in the tube changes rapidly with time which produces large variations in the wavelength - and thus the amplitude distribution of the standing wave. Hence the observed large amplitude variations during these two phases is to be expected. What is not expected at a given location is the large fluctuations in amplitude of over ten decibels during the quasi-steady burning period when the temperature in the tube has nearly reached steady state. Also, as shown in Fig. 6, the phase differences between the transducer signal and the Ling driver changes rapidly during this period. As reported in Ref. 6, this phase data indicate that the solid propellant combustion process is randomly driving and damping the oscillations.

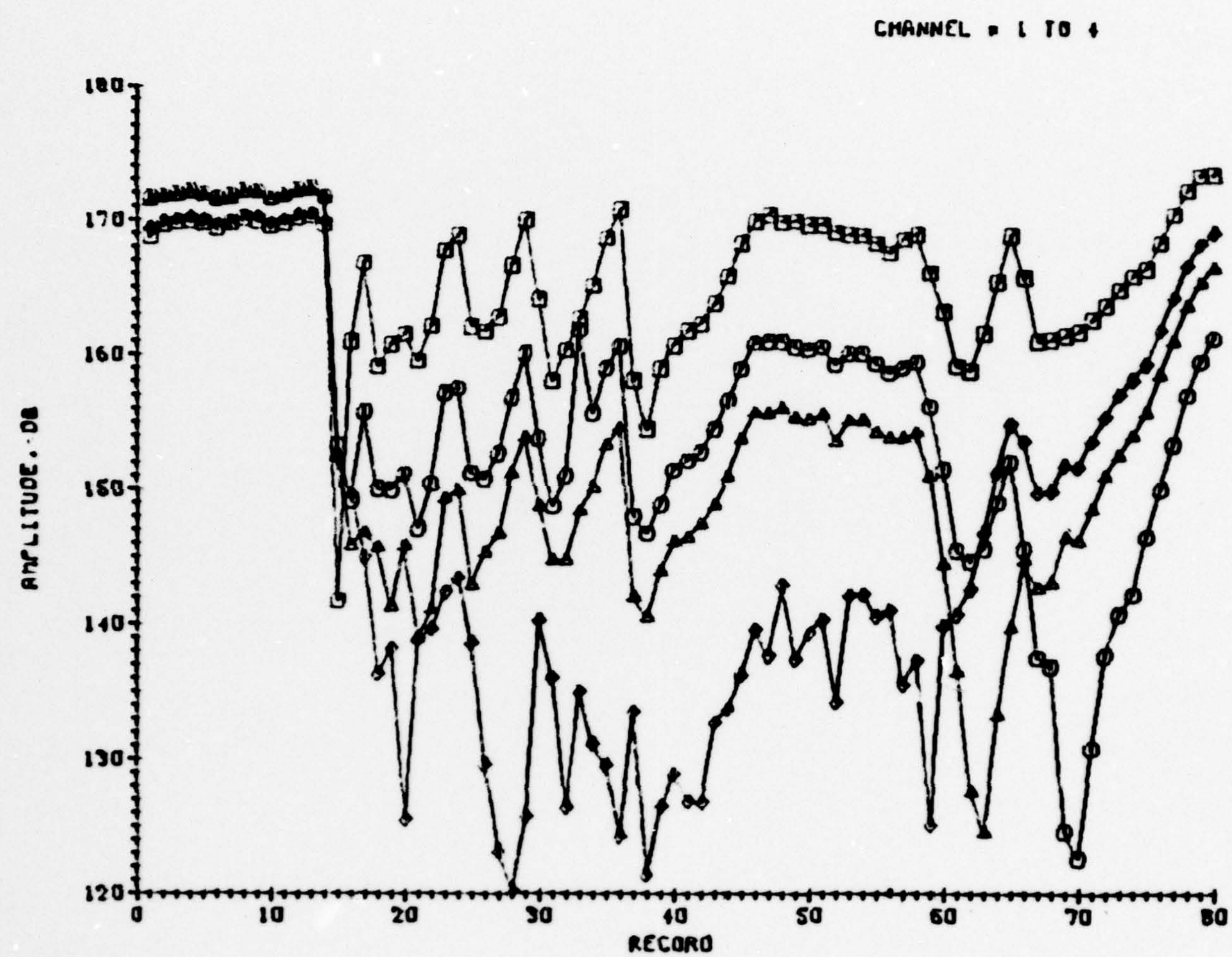

Figure 5. E-16-633-590.A-13.742MZ..300PSID.CLOSED END.

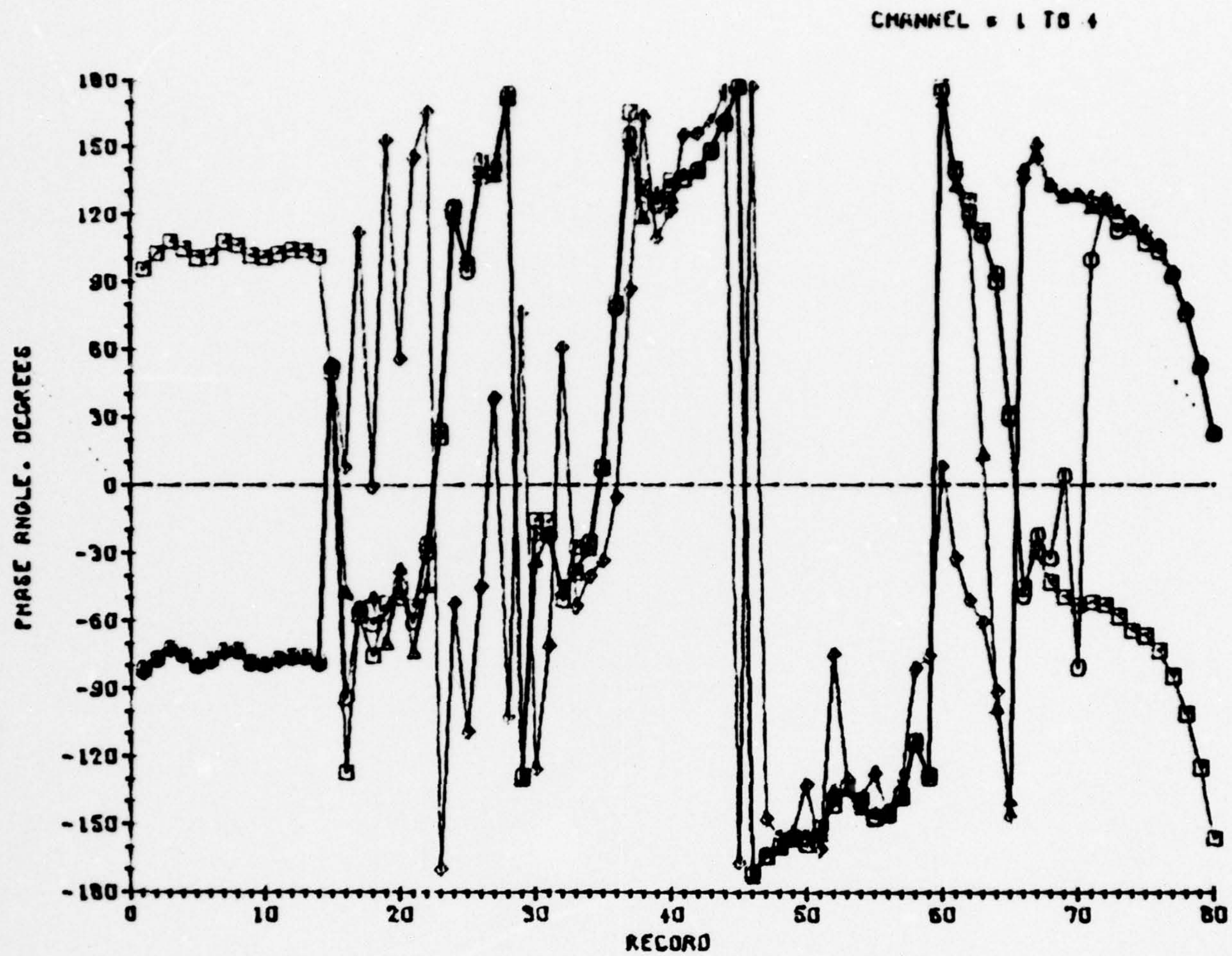

Figure 6, E-16-633-590.A-13.742HZ..300P810.CLOSED END.

This anomalous behavior of the amplitudes and phases has been investigated intensively during the past year. The fluctuations can lead to significant errors in the pressure data. The digital filtering performed by the minicomputer-based data acquisition system assumes that the amplitude of the signal either remains constant or varies randomly during a sampling interval. If the signal amplitude either increases or decreases monotonically during the interval, errors in both the filtered amplitude and phase will occur. To ensure data accuracy during the quasi-steady burn period, methods for eliminating these fluctuations have been investigated.

Over the report period, 82 tests have been conducted to study the effect of (1) low and high power output of the acoustic drivers, (2) propellant composition, (3)exhaust end configuration, and (4) burner tube length on the amplitude variations during the burn. In addition, methods of improving transducer accuracy and ensuring uniform and instantaneous ignition have been investigated.

In the first series of tests, the effect of the acoustic power output - and thus the amplitude of the standing wave at the propellant face - on the combustion response was investigated for propellant B (Propellant B was provided for testing by the Thiokol Corporation; its composition is not known), a highly unstable propellant when used in T-burners. It was found that the propellant exhibited qualitatively the same behavior for both low and high power outputs. The large fluctuations in amplitude at a given location, the random driving and damping behavior as exhibited by the phase were present regardless of the magnitude of the peak amplitude of the standing wave.

The propellants in almost all tests conducted to date at 300 psig exhibited apparent driving at some times and damping at others.* The most unstable propellants - A-15 and propellant B- appear to exhibit the largest variation from driving to damping whereas the most stable propellant T-13 seems to show the least.

Further tests were conducted with a constant tube length and various exhaust end configurations as reported in Ref. 6. Although the amplitude variations can be decreased somewhat by changing the termination at the exhaust end, the random driving - damping behavior exhibited by the phase data is evident and it increases with increasing frequency. One test at a low frequency (280 Hz), however, did not exhibit this behavior and driving of the acoustic oscillations by the combustion process was indicated throughout the burn. This run gave the most consistent results in that the propellant exhibited constant properties over the burn period.

Because of the frequency dependence of the variation in the pressure amplitude during the burn, the following explanation of this behavior was put forth. The tube length in all runs was seven feet. Prior to ignition a series of pressure amplitude maxima and minima one-half wavelength apart exist between the sample and the acoustic driver. The positioning of the driver with respect to a maximum or minimum determines the overall amplitude of the standing wave. Changing this position changes the peak amplitude of the standing wave from a maximum at resonance to a minimum at off-resonant conditions. When the propellant sample is ignited, the temperature in the tube increases, which increases the wavelength. At the higher fre-

*It is quite possible that when gas phase acoustic losses in the driven tube are taken into consideration, the apparent damping may actually turn out to be a driving condition.

quencies several maxima and minima may pass by the driver after ignition which produces the large amplitude variations during a burn and as shown in Fig. 5. By decreasing the length between the acoustic driver and the tested propellant sample, the number of successive maxima and minima in between is reduced and thus less variation in the amplitude during a test should result.

Tests run with short tubes confirm this explanation. Amplitude and phase data are presented in Figs. 7 and 8 respectively for an A-13 propellant at 600 Hz with the acoustic driver 39 inches from the propellant face. In Figs. 5 and 6 the distance is 96 inches. After the ignition period (records 13 to 16) the amplitude slowly varies until relatively constant levels are reached from record 40 to 80. The burnout occurs after the time period over which these data were taken. The corresponding phase data exhibit the same behavior - varying slowly from record 17 to 40 and then remaining relatively constant with reference to the driver signal. However, the random driving - damping behavior previously experienced in the phase data is still present though at a reduced level.

A series of tests were conducted to investigate the observed random nature of the phase data. During these tests the digital data were compared with the correspondent analog data recorded on a tape recorder and played back at reduced speed. It was found from this comparison that the computerized data acquisition system was the source of the driving - damping behavior. When filtering the data, it is necessary to take samples over sufficiently long time periods to average out any noise or random amplitude fluctuations that are present in the signal so that only the sinusoidal signal remains. However, because of the short duration of the burn, the time over which the signal is filtered is insufficient to adequately

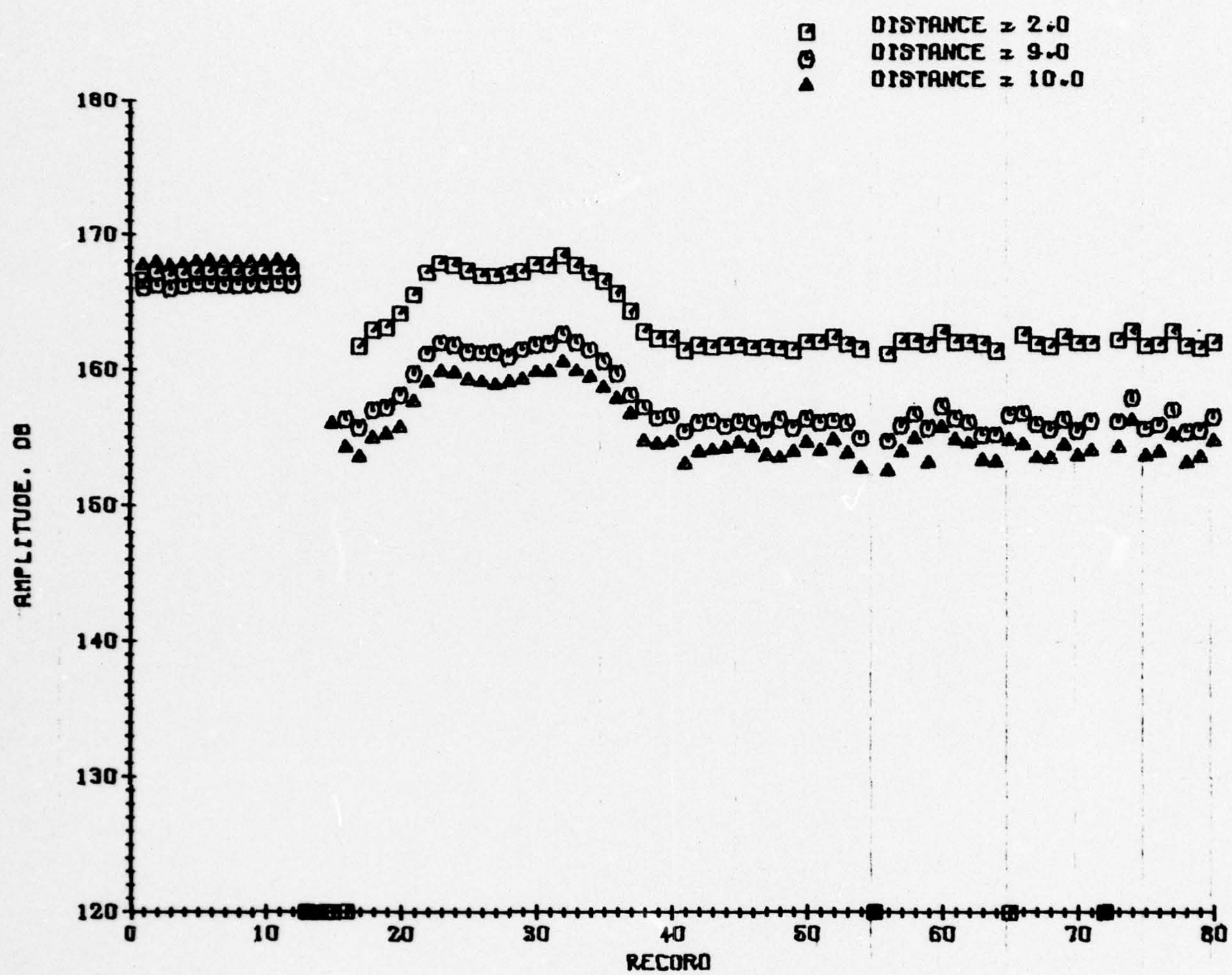

Figure 7. E16-633-714, A-13, 600HZ, DRIVER @ 39°

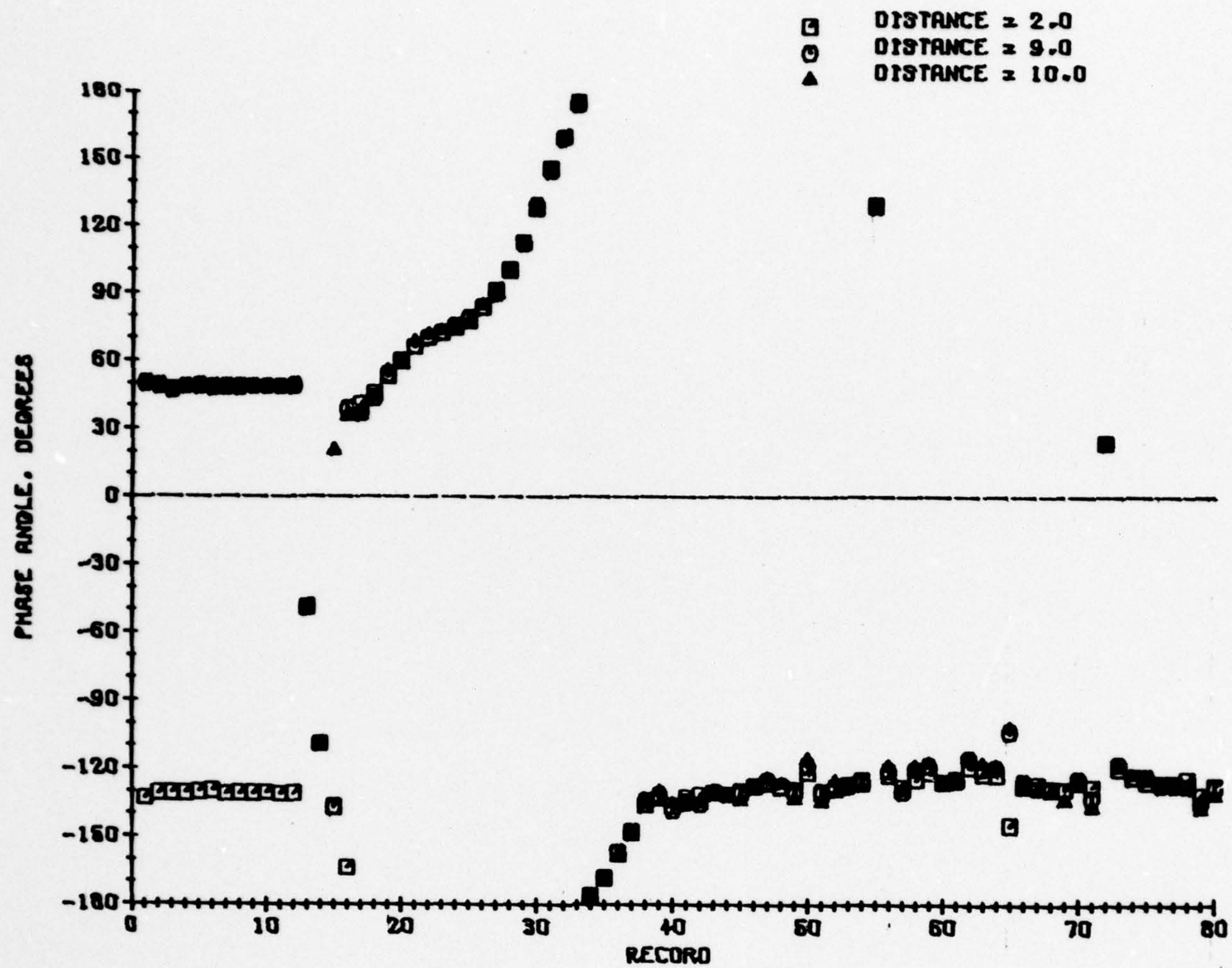

Figure 8. E16-633-714. A-13. 600HZ. DRIVER = 39"

average out the noise or any random fluctuations in amplitude. Therefore, small errors in phase can result. As mentioned earlier in this section, for the low admittances characteristic of burning solid propellants, small phase differences along the standing wave are to be expected. Therefore, the phase errors can lead to erroneous conclusions as to the propellants driving or damping behavior. In a related study[7,8] of the response of liquid rocket injector configurations, this data acquisition system gives excellent results. This is due to the fact that the injector tests are of sufficient duration to ensure accurate digital filtering.

Because of the difficulties in filtering the transducer data during the short burn times associated with the propellant tests, the data are first recorded on a 14-channel Ampex tape recorder. The signals are then played back at reduced speed which, in effect, lengthens the test period. The signals are then filtered using a long sampling interval to obtain reliable pressure amplitude and phase data.

In addition to the aforementioned tests, additional tests were conducted to determine the ignition and burnout characteristics of the propellant sample and tests to determine the admittance at the "driven" end of the tube. Twenty tests were conducted to determine the ignition and burnout characteristics of a typical propellant to assure uniform burning over the propellant face. Two methods of ignition were investigated. The first consisted of imbedding a nichrome wire in the igniter paste in an "S" shape. This method has been the standard technique used in this study. The second method, commonly used in T-burners, was to spread the igniter paste over the sample. In the center of the sample, the nichrome wire was imbedded in a spot of paste dabbed onto the surface. At atmospheric pressure the "S" configuration ignited the sample almost instantaneously in a uniform

manner over the propellant face. The sample appeared to burn evenly and the flame front remained uniform throughout the burn. In the test with the "spot" ignition, the electric match ignites the propellant almost explosively but the flame does not spread uniformly across the sample face. This igniter did not ignite the propellant as rapidly as the "S" configuration. Also, the burnout was not uniform and on many occasions the electric match ignited one side of the propellant before the other which caused uneven burning. Even under the best conditions, the ignition occurred at the match and the propellant center ignited before the remainer of the surface causing a concave burning surface which produced uneven burnout. As a result of these tests, the "S" ignition technique will continue to be used.

Current research efforts are directed at improving and maintaining the accuracy of the measured data. Extensive checkouts of the tape recorder system are being conducted, and testing will resume upon completion. The classical impedance tube technique has been successfully modified for high temperature and pressures with mean flow present in the tube. The proper operation of the method has been demonstrated in a related study of liquid rocket injectors; and,once the accuracy of the measured data in the research described in this report is improved, the technique should yield reliable results.

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